EARTH SURFACE PROCESSES AND LANDFORMS, VOL. 21, 181–193 (1996)

AGGREGATE STABILITY OF SOILS IN CENTRAL SPAIN AND THE ROLE OF LAND MANAGEMENT

J. L. TERNAN, A. G. WILLIAMS, A. ELMES AND R. HARTLEY

Department of Geographical Sciences, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, UK

Received 6 October 1994
Accepted 11 March 1995

ABSTRACT

The paper examines the relationships between soil aggregate stability, selected soil properties and land use in central Spain. Aggregate stability indices derived from three procedures were found to be significantly ($p > 0{\cdot}01$) correlated with each other as well as with clay content, organic carbon and a range of water-soluble salts. Soils with a higher clay content have a lower aggregate stability. It appears that the presence of expandable clays has a major negative influence, although this impact is strongly modified by recent land-use history and contemporary land-management practices. Agricultural land, abandoned in the 1940s, was subsequently invaded by *Cistus* matorral or planted with *Pinus*. The most stable aggregates occur under matorral and may represent a lag of more resistant aggregates surviving past land-use-related erosional processes. Comparisons with aggregates under *Pinus* however suggest that hydrophobic substances from the *Cistus* may have increased aggregate stability. Aggregates from areas remaining in cultivation are the least resistant although the stability envelope overlaps with areas under *Pinus*. These differences may be related to cultivation practices whereby clay-rich subsurface horizons characterized by higher proportions of expandable clays are drawn to the surface, and to enhancement of aggregate stability under forest by fungal hyphae.

KEY WORDS aggregate stability; land management; soil properties; clay mineralogy

INTRODUCTION

The stability of soil aggregates is a major factor controlling topsoil permeability and erodibility (De Ploey and Poesen, 1985; Bryan *et al.*, 1989). Numerous studies (e.g. Imeson and Jungerius, 1976) have demonstrated linkages between land use and management and the physical, chemical and micromorphological properties of soils which determine aggregate stability. In central Spain concern over land degradation led to extensive *Pinus* afforestation in the 1950s, initially on abandoned cultivated land. Nearby areas were either colonized by *Cistus*-dominated matorral scrub or remained under cultivation. In the 1980s formerly cultivated land under matorral was bench-terraced and afforested with *Pinus* involving considerable soil disturbance and erosion (González del Tanago *et al.*, 1994). The data presented in this paper are concerned with an evaluation of the major influences on aggregate stability in the area. Although raindrop impact is unlikely to be a significant erosion process under mature forest or matorral such data are important in predicting land degradational impacts of possible future land-use changes. The need to assess such potential land degradational impacts is particularly important in Spain where much of the land is climatically and economically marginal in terms of agricultural production, and where there is continued pressure to convert matorral lands to forest.

THE STUDY AREA AND SAMPLING DESIGN

The results reported here are for soils in the Puebla de Beleña–Puebla de Valles–Retiendas area of west Guadalajara province (Figure 1) at an altitude of around 1000 m. The soils are developed on Tertiary to early

CCC 0197-9337/96/020181-13

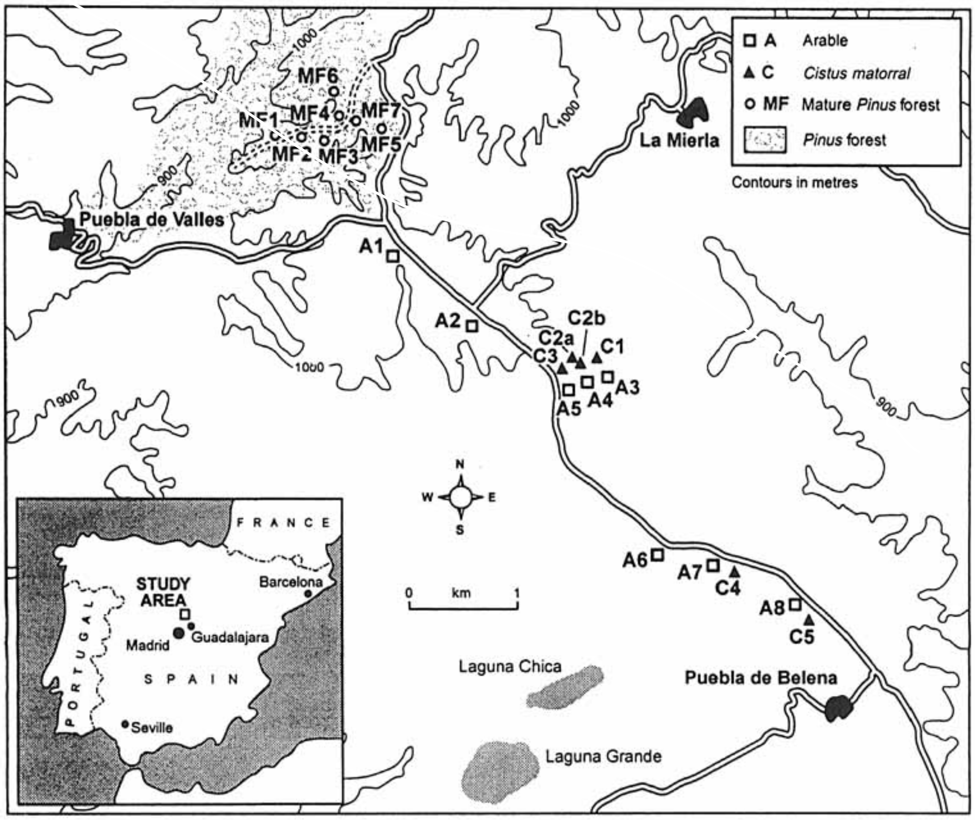

Figure 1. Location of field area and soil sampling sites

Quaternary alluvial deposits of the Raña formation, and constitute the divide area between the Rio Jarama and Rio Sorbe. Incision of these two rivers and their tributaries into the Raña surfaces has created a sequence of terraces (Pérez-González and Gallardo, 1987) separated by steeper, frequently extensively gullied slopes. Erosion is active and despite a good vegetation cover parts of the area have developed a distinctive badland type of landscape. The area receives around 700–800 mm of rain per annum (Muñoz *et al.*, 1989) but is seasonally arid. Summer temperatures frequently exceed 35°C and potential evapotranspiration exceeds precipitation from May to September.

The predominant soils in the area may be classified as Alfisols and have distinctive argillic (Bt) horizons (Espejo Serrano, 1985) often with evidence of pseudogleying (Gallardo *et al.*, 1987). The fine-earth fraction is mainly of silt-loam texture and the stone content varies greatly. The soils are non-calcareous and the pH ranges from 5·6 to 6·5. To minimize problems arising from interpreting data from widely different parent materials all samples were collected from gently sloping (< 5°) sites, from soils developed on sediments of mapping unit 28 of the 1 : 50 000 Mapa Geologica de España – Valdepeñas de la Sierra. A range of sampling sites were selected under 30–40 year old *Pinus pinaster*, *P. nigra* forest, mature *Cistus* matorral, and cereal cultivation. Within the forest a shallow litter layer provides some protection to the soil surface. This litter layer is however extremely variable depending on tree density, slope and disturbance by local fauna including mushroom harvesters in the autumn. A good litter and lichen crust is present under areas of undisturbed matorral, but where local damage to the matorral has occurred through scrub clearance or overgrazing, the soil surface is left unprotected. At the time of sampling the ground surface on cultivated land was very cloddy following recent ploughing. The patchwork of *Cistus* matorral and cultivated land in the area

permitted soil sampling of these two land uses at sites only a few metres apart. All sampling was carried out in the early summer to minimize problems arising from temporal variability in aggregate stability (Imeson and Vis, 1984; Blackman, 1992). Results reported here are mainly for the surface (0–10 cm) horizon at 20 locations selected as representative from a larger data set for the area as a whole.

SOIL PROPERTIES AND THE ASSESSMENT OF AGGREGATE STABILITY

Various studies (Bryan, 1976; Grieve, 1980a) have highlighted the influence of wetting technique on tests of soil structural stability. Consequently in this investigation three methods of aggregate stability assessment were adopted: a flood-wetting procedure to determine the percentage of water-stable aggregates, a waterdrop test, and a laboratory rainfall simulation technique.

Water stable aggregates

The use of a flood-wetting procedure to determine the percentage of water-stable aggregates may be a particularly appropriate technique for simulating conditions in central Spain where wetting of the soil surface from a relatively dry state is very rapid (Grieve, 1980a). Furthermore, Bryan considers that flood-wetting of air-dried soil maximizes slaking breakdown which he argues (Bryan, 1968) is an important erosional process only on dry soils. Slaking breakdown also minimizes stresses set up by unidirectional wetting or differential hydration, stresses which may be particularly significant in soils with expandable clays, as in central Spain. The procedure followed was modified from Yoder (1936). A 100 g sample of air-dried soil was placed on a stack of 0·5 and 3·0 mm mesh sieves, and agitated in deionized water in a sink using the apparatus described by Grieve (1979). Soil remaining on the sieves was transferred to beakers and dried at 105°C. After deducting the weight of sand, gravel and coarse organic matter, the weight of water-stable aggregates $> 3{\cdot}0$ mm (WSA $> 3{\cdot}0$) and $> 0{\cdot}5$ mm (WSA $> 0{\cdot}5$) was expressed as a percentage of the original weight of soil (*c.* 100 g). Bryan (1968) found these to be the most efficient indices of erodibility from a range tested.

Waterdrop test

It has been argued (Bryan, 1968) that aggregates shown to be water-stable by the gentle slaking action of wet sieving may not in fact be water-stable when subject to high-velocity rainfall. Furthermore, raindrop action is considered to be one of the principal agents for the detachment and subsequent transport of soil material. Consequently many researchers (De Meester and Jungerius, 1978; Imeson and Verstraten, 1985) have chosen to measure aggregate stability on the basis of their response to falling waterdrops. The second procedure adopted in this study therefore follows that of Low (1954). Twenty-five 4·0–5·6 mm air-dried aggregates from each site were subject to impacts from waterdrops falling *c.* 1·0 m from a burette fitted with a constant-head device. The average number of drops to breakdown was calculated as the aggregate stability index.

Laboratory rainfall simulator

The problems of defining the most suitable erodibility index based on drop-test data have been highlighted by Bergsma and Valenzuela (1981), and Farres (1980) has demonstrated the effect of drop frequency in determining time to breakdown. Furthermore, Grieve (1980a) argues that drop tests probably overestimate the weakness of surface structures to rain impact by overestimating the energy input through concentrating on single drops. Consequently Ternan *et al.* (1994) developed a third procedure for testing soil aggregates in terms of their response to simulated rainfall using a laboratory rainfall simulator inside an environmental chamber. Twenty-five air-dried aggregates were placed on a 2·8 mm sieve and equilibrated for 24 h at 50 per cent relative humidity to ensure similar initial soil-moisture status. Rainfall was simulated at *c.* 45 mm h^{-1} intensity with a mean drop size of 580 μm (SD 250 μm) as determined by the filter-paper technique adopted by Mason and Andrews (1960). The percentage of water-stable aggregates surviving at 0·5 min intervals was determined and aggregate breakdown curves plotted (Figure 2). A mean rainfall simulation survival index (RSSI) was calculated based on the number of aggregates surviving at 5, 10, 15 and 20 min during the test.

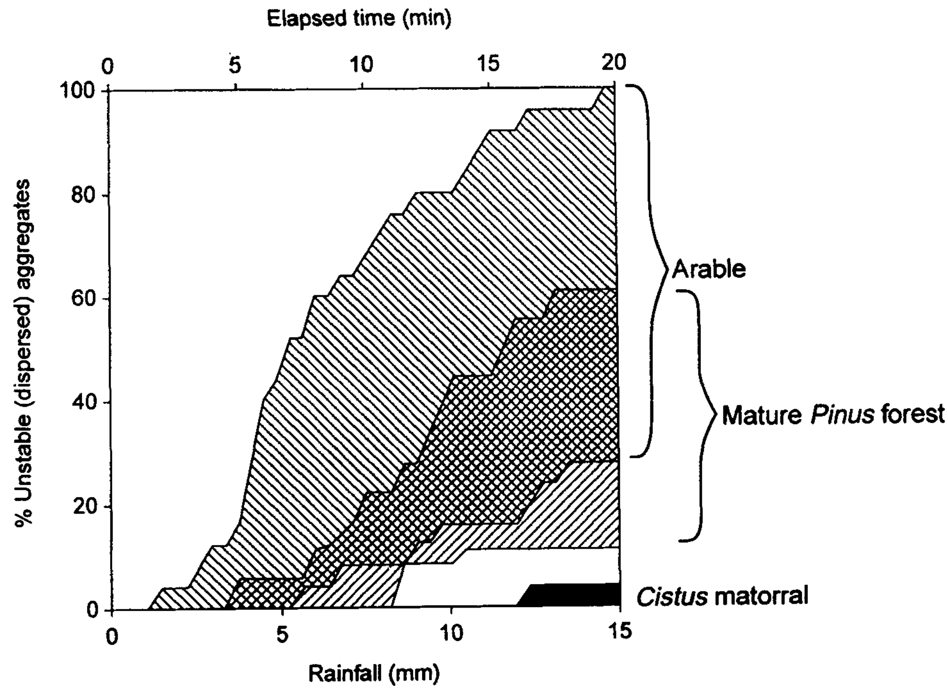

Figure 2. Aggregate stability fields derived from laboratory rainfall simulation test. Percentage dispersed aggregates determined during twenty-second breaks after each of forty thirty-second bursts of simulated rain

Correlation of results

The correlation matrix (Table I) demonstrates a good relationship between the three procedures. The correlations between the flood-wetting parameters (WSA > 3·0, WSA > 0·5) and the RSSI were highly significant ($p > 0{\cdot}001$) and the drop test, although still significantly correlated ($p > 0{\cdot}01$), appeared to be somewhat less related, possibly due to the effect of a few resistant aggregates distorting the index (Bergsma and Valenzuela, 1981).

Other soil properties

The size distribution of the fine-earth fraction was determined by a combination of wet sieving (> 63 μm fraction) and sedimentation techniques (< 63 μm fraction). Samples were pretreated with 9 per cent H_2O_2 to remove organic matter and soaked in Calgon for a minimum of 6 h. For silt and clay determination subsamples were additionally ultrasonically dispersed for a period of 15 min prior to analysis by standard pipette procedure (BSI 1975). The organic carbon content of the silt and clay (< 63 μm) fraction was

Table I. Correlation matrix for aggregate stability indices (all correlations significant at 0·01 level)

	WSA > 3 mm	WSA > 0·5 mm	Average number of drops	RSSI
WSA > 3 mm	—	0·996	0·763	0·865
WSA > 0·5 mm	—	—	0·742	0·860
AV.DROP No.	—	—	—	0·621

measured by high-temperature catalytic oxidation with non-dispersive infra-red detection (Sugimura and Suzuki, 1988) using a Shimadzu TOC 5000. In addition, to obtain a crude index of the total amount of coarse and fine organic matter present, weight-loss-on-ignition was determined at 350°C for the fine-earth fraction (< 2·00 mm). Soil pH, EC_{25} and water-soluble salts were determined for 1 : 1 soil-water mixtures (Cammeraat, 1991). Concentration of K^+ and Na^+ were analysed by flame photometry, Ca^{2+} and Mg^{2+} with an atomic absorption spectrophotometer, and SO_4^{2-}, Cl^- and total organic nitrogen colorimetrically with a Technicon Autoanalyser II. The clay mineral content of the < 2 μm fraction of selected soil horizons was carried out by semi-quantitative X-ray diffraction analysis.

AGGREGATE STABILITY AND SOIL PROPERTIES

The results of aggregate stability tests and analyses of soil properties are presented in Tables II–IV. Correlation analysis was used as a means of exploring possible relationships between aggregate stability parameters and measured soil properties. Results from analyses of drop-test data were generally less significant statistically (Table I), and the following review focuses primarily on the water-stable aggregate (WSA) and rainfall simulation indices.

Soil texture

The fine-earth fraction of all soils was dominated by silt- and sand-sized material. Clay content ranged from 2 to 28 per cent and was significantly higher in areas under arable cultivation. Statistical analysis revealed significant ($p > 0{\cdot}01$) negative correlations (Table V, Figure 3) between WSA > 3·0, WSA > 0·5,

Table II. Soil texture, % organic carbon and % loss on ignition for the 0–10 cm horizon under arable cultivation, *Cistus* matorral and *Pinus* forest

Sample No.	% of fine earth fraction < 2 μm	2·63 μm	63 μm–2·00 mm	% Organic Carbon (of < 63 μm fraction)	% Loss on Ignition (of < 2·00 mm fraction) 350°C
Arable Soils					
A1	16·0	59·0	25·0	0·6	1·7
A2	11·7	50·7	37·6	1·2	2·2
A3	18·1	49·4	32·5	0·4	1·4
A4	15·0	56·9	28·1	0·5	2·9
A5	14·4	48·1	37·5	0·5	1·1
A6	28·0	54·1	17·9	0·4	1·2
A7	26·7	37·8	35·5	0·7	1·2
A8	18·8	41·1	40·1	1·0	1·1
Cistus/Rosmarinus matorral					
C1	5·5	49·4	45·1	1·6	1·6
C2a	6·0	51·0	43·0	1·1	1·9
C3	10·0	52·1	37·9	1·3	3·4
C4	5·4	38·9	55·7	3·4	2·6
C5	7·2	47·9	44·9	1·9	5·3
Mature Forest *Pinus pinaster* & *P. nigra*					
MF1	4·6	70·1	25·3	2·0	2·4
MF2	2·1	24·6	73·3	0·8	1·9
MF3	4·8	32·9	62·3	1·0	1·9
MF4	6·2	49·8	44·0	1·9	3·0
MF5	4·6	38·5	56·9	1·6	2·6
MF6	7·7	45·3	47·0	—	4·1
MF7	5·5	32·7	61·8	2·3	5·1

Table III. Selected chemical characteristics of the 0–10 horizon under arable cultivation, *Cistus* matorral and *Pinus* forest

Sample No.	pH	EC_{25} $mScm^{-1}$	Na^+	K^+	Ca^{2+}	meq/100 g sample Mg^{2+}	Cl^-	TON	SO_4^{2-}
Arable Soils									
A1	5·9	0·204	0·196	0·051	0·778	0·215	0·175	0·3219	0·315
A2	6·4	0·160	0·174	0·064	0·634	0·131	0·203	0·1574	0·280
A3	5·7	0·384	0·326	0·064	1·492	0·375	0·621	0·4807	0·222
A4	5·7	0·391	0·174	0·077	1·592	0·368	0·276	0·5871	0·349
A5	5·7	0·105	0·109	0·051	0·344	0·098	0·017	0·0681	0·247
A6	7·0	0·140	0·196	0·038	0·479	0·156	0·028	0·0326	0·525
A7	6·7	0·114	0·174	0·026	0·454	0·087	0·155	0·0365	0·096
A8	5·9	0·199	0·152	0·077	0·948	0·164	0·107	0·2497	0·083
Cistus/Rosmarinus matorral									
C1	5·6	0·260	0·261	0·729	0·993	0·313	0·863	< 0·0001	0·540
C2a	5·7	0·443	0·544	0·972	2·205	0·477	0·812	< 0·0001	0·769
C3	6·4	0·445	0·522	0·384	2·081	0·528	0·282	< 0·0001	0·870
C4	6·7	0·659	1·175	1·509	3·340	0·513	1·608	0·0073	0·814
C5	6·5	0·492	0·544	1·074	2·280	0·393	0·536	< 0·0001	0·573
Mature Forest *Pinus pinaster* & *P. nigra*									
MF1	6·2	0·181	0·783	0·652	0·550	0·357	0·671	0·0003	0·620
MF2	6·5	0·164	0·609	0·332	0·540	0·410	0·653	0·0047	0·541
MF3	5·8	0·206	1·066	0·345	0·523	0·518	0·967	0·0006	1·112
MF4	7·5	0·195	0·544	0·294	0·569	0·174	0·558	0·0516	0·575
MF5	5·6	0·146	0·674	0·345	0·444	0·245	0·584	0·0111	0·379
MF6	7·3	0·192	0·609	0·358	0·585	0·139	0·591	0·0327	0·627
MF7	6·5	0·200	0·696	0·281	0·554	0·549	0·682	0·0070	0·456

RSSI and clay per cent. The stability of soil aggregates depends on the balance of disruptive as opposed to stabilizing forces (De Meester and Jungerius, 1978) and the amount of clay is usually recorded as having a stabilizing influence (De Ploey and Poesen, 1985). Clays such as illite and smectite however readily form aggregates, but their swelling and shrinkage characteristics render such aggregates less stable than those formed from kaolinite (Morgan, 1986). Significant proportions of both illite and smectite occur in soils of this region (Vardour, 1979) and analyses presented in Table VI confirm their presence and dispersive impact. A reduction in stabilizing influences, such as organic matter, through adverse land management practices may therefore be critical.

Organic matter

The organic carbon content of the $< 63\,\mu m$ fraction was generally between 1 and 4 per cent although it tended to be lower in cultivated soils (Table II). The correlation analysis indicated a significant ($p > 0{\cdot}01$) positive correlation between all the aggregate stability indices and organic carbon, although there is a considerable scatter in the data (Figure 4). Correlations between indices based on the flood-wetting procedure are stronger than those based on drop-test and rainfall simulation methods. This suggests that organic matter is important in reducing disruption arising from slaking pressures but may not be as effective in preventing aggregate breakdown by raindrop impact. Correlations between aggregate stability indices and loss-on-ignition data for the $< 2{\cdot}00$ mm fraction were either not significant, or at a lower level of significance than the organic carbon data, suggesting that coarse organic matter may have a less beneficial effect on aggregate stability than finer material. There is a broad consensus on the beneficial effects of organic matter although as Tisdall and Oades (1982) identify, the relationships are not always clear. Results reported here are broadly in accord with those found elsewhere in Spain (e.g. Imeson and Verstraten, 1985).

Table IV. Aggregate stability indices for the 0–10 cm horizon under arable cultivation, *Cistus* matorral and *Pinus* forest

Sample No.	Aggregate stability indices % WSA > 0·5	% WSA > 3	water-drop test (average number of drops)	Rainfall simulation % R.S.S.I.
Arable Soils				
A1	1·2	0·3	12·0	39·0
A2	11·6	16·8	33·0	64·7
A3	5·8	4·2	13·0	39·0
A4	2·9	0·8	31·0	56·0
A5	4·4	5·1	37·0	87·0
A6	0·5	0·2	44·0	39·0
A7	1·3	0·7	73·0	31·0
A8	3·8	4·0	34·0	74·0
Cistus/Rosmarinus matorral				
C1	86·6	96·4	224·0	99·0
C2a	90·8	100·0	555·0	100·0
C3	83·5	94·8	314·0	100·0
C4	89·0	95·2	520·0	100·0
C5	87·1	95·3	215·0	100·0
Mature Forest *Pinus pinaster* & *P. nigra*				
MF1	68·9	69·0	156·0	85·0
MF2	65·3	63·5	81·0	93·1
MF3	58·8	62·1	143·0	87·5
MF4	32·6	29·8	34·0	66·7
MF5	74·5	72·2	146·0	90·0
MF6	46·2	52·1	25·0	83·8
MF7	80·7	82·9	108·0	89·3

Table V. Correlation coefficients for aggregate stability indices with measured soil properties

	WSA > 3 mm	WSA > 0·5 mm	Average number of drops	R.S.S.I.
% Clay (< 2 μm)	−0·783	−0·805	−0·425	−0·823
% Silt (2–63 μm)	−0·198	−0·221	−0·037	−0·252
% Sand (63–2000 μm)	0·483	0·504	0·290	0·587
% Organic carbon	0·689	0·700	0·556	0·592
% LOI 350°C	0·518	0·519	0·133	0·426
pH	−0·011	−0·010	−0·114	−0·112
EC_{25}	0·491	0·465	0·721	0·355
Na^+	0·688	0·717	0·535	0·577
K^+	0·805	0·797	0·852	0·682
Ca^{2+}	0·466	0·436	0·761	0·350
Mg^{2+}	0·702	0·710	0·619	0·542
Cl^-	0·702	0·717	0·655	0·550
TON	−0·644	−0·642	−0·438	−0·591
SO_4^{2-}	0·697	0·688	0·598	0·591

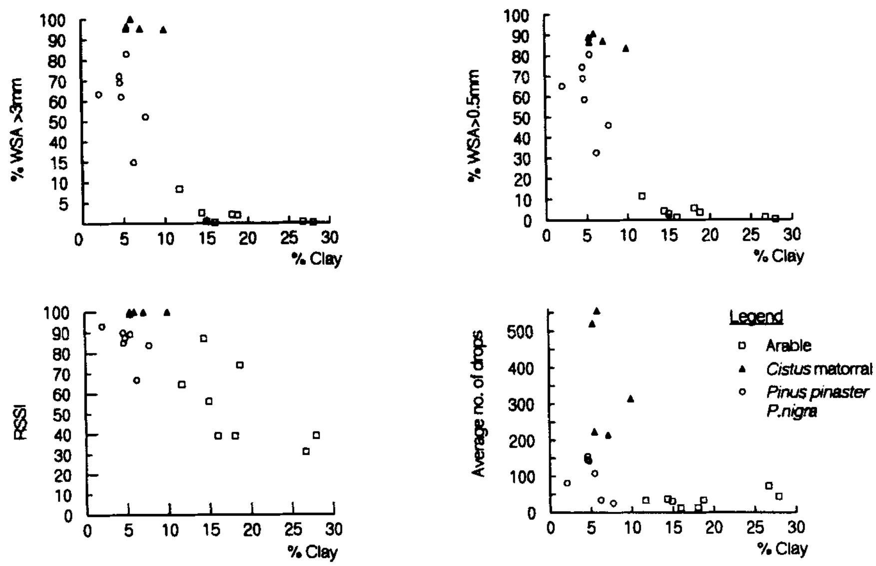

Figure 3. Relationships between aggregate stability indices and clay content

Water-soluble salts

The relationships between water-soluble salts and aggregate stability are difficult to interpret. The low electrolyte concentrations ($EC_{25} < 0{\cdot}5\,mS\,cm^{-1}$) indicate a chemically non-dispersive environment (Imeson *et al.*, 1982), and the statistical analysis shows significant positive correlations ($p > 0{\cdot}01$) between aggregate stability parameters and dissolved species (Table V). This may be a reflection of land-use influences, well-vegetated areas having higher concentrations of K^+, Na^+, Mg^{2+}, Cl^- and SO_4^{2-}. These higher soluble-salt concentrations may be the result of litter decomposition and nutrient turnover. Additionally, although located in central Spain, atmospherically derived salts may be trapped by vegetation and accumulated in the surface soil horizons by high evaporation rates and a lack of deep circulation of soil water. The generally higher soluble-salt concentrations recorded in the upper horizons of an undisturbed *Cistus* matorral profile (Table VII) provide some support for this interpretation.

LAND USE AND AGGREGATE STABILITY

It is clear from Table IV that land use is a major influence on topsoil aggregate stability in the Puebla de

Table VI. Semi quantitative XRD analysis of $<2\,\mu m$ fraction of undisturbed profile under *Cistus* matorral (site C2b) and adjacent Ap horizon (site A_4) under cereal cultivation. Smectite dominant 'expandable' at 20–30 cm depth under *Cistus*

	Cistus—Matorral			Arable		
Horizon Depth	Illite	Expandable %	Kaolinite	Illite	Expandable %	Kaolinite
0–10 cm	69	11	20	} 53	24	23
20–30 cm	36	43	21			

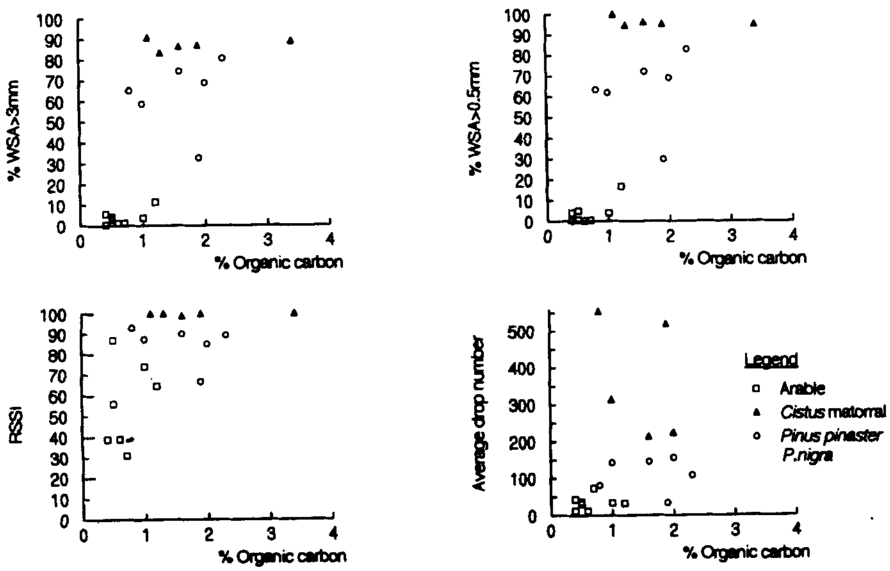

Figure 4. Relationships between aggregate stability indices and organic carbon content

Beleña–Puebla de Valles region. Soils under cereal cultivation show the lowest aggregate stability with most samples having WSA > 3·0 and > 0·5 of less than 5 per cent, and rapid breakdown under both the waterdrop and rainfall simulation tests. Soil aggregates under mature *Pinus* forest could be classified as moderately resistant, with the stability envelope derived from the rainfall simulation test (Figure 2) overlapping that of the arable soils. By contrast, the most stable aggregates were found under *Cistus–Rosmarinus* matorral with the WSA > 3·0 and > 0·5 exceeding 80 per cent. Under the drop test these aggregates were only very slowly physically broken down. The rainfall simulation stability envelope shows a clear separation of these aggregates from those of the forest and arable soils, with almost all the aggregates surviving the simulation.

Matorral

The high stability of topsoil aggregates from matorral areas would appear to be directly and indirectly a reflection of the clay content. The low clay content of the 0–10 cm horizon may be attributed to previous dispersion of less resistant aggregates and the removal of dispersed material by rainsplash and overland flow processes or possibly by eluviation. These aggregates may therefore represent a lag of resistant aggregates within a sandy surface matrix. These processes may have occurred in the immediate post-abandonment period as the evidence for contemporary erosional losses under mature *Cistus* matorral is minimal. Furthermore, the presence of lag gravels with good lichen growth on the clasts, and a well-developed lichen crust point to the importance of past rather than contemporary erosion events. Further work is needed on the properties of the aggregates under *Cistus*. Aggregates tested in the laboratory showed very slow rates of water uptake and may be considered hydrophobic, possibly due to sticky exudates from the *Cistus*. In the field, however, the soil surface, comprising both aggregates and dispersed soil material, showed little evidence of hydrophobicity, and water droplets were almost immediately absorbed. Experimental work by Sullivan (1990) argues that a non-uniform distribution of hydrophobic organic matter in virgin soil aggregates at the submicroscopic scale reduces water-uptake rates because of a greater amount of air encapsulation. Furthermore, Bryan (1976) has observed that in some cases colloidal humus may be deposited so that aggregates are partially waterproofed giving rise to variable water penetration. Such impedance of water penetration reduces the effectiveness of slaking.

Table VII. Aggregate stability indices and soil properties for *Cistus* matorral profile at site C2b

Horizon Depth	% of fine earth fraction			% Carbon Content (of $<63\,\mu m$ fraction)	Organic Matter % Loss on Ignition (in $<2\cdot00\,\mu m$ fraction)
	$<2\,\mu m$	$2–63\,\mu m$	$63\,\mu m–2.00$ mm		350°C
0–10 cm	10·2	59·8	30·0	0·4	0·7
10–20 cm	27·4	50·8	21·8	0·3	0·6
20–30 cm	32·8	43·9	23·3	0·2	0·7
30–40 cm	32·2	41·6	26·2	0·2	0·6
40–50 cm	32·3	41·2	26·5	0·2	0·7

Horizon Depth	pH	EC25 mScm-1	meq/100 g sample						
			Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	TON	SO_4^{2-}
0–10 cm	6·4	0·098	0·609	0·230	0·172	0·056	0·366	0·0237	0·774
10–20 cm	6·4	0·069	0·522	0·107	0·146	0·040	0·486	0·0073	0·235
20–30 cm	6·2	0·056	0·457	0·033	0·132	0·069	0·173	0·0040	0·135
30–40 cm	6·2	0·060	0·457	0·026	0·119	<0·001	0·153	0·0083	0·191
40–50 cm	6·3	0·075	0·892	0·031	0·187	<0·001	0·242	0·0149	0·285

Horizon Depth	Aggregate stability indices			Rainfall simulation % R.S.S.I.
	% WSA > 0·5	% WSA > 3	Water drop test Average number of drops	
0–10 cm	20·3	21·2	140·0	75·0
10–20 cm	8·3	1·8	125·0	92·5
20–30 cm	4·9	1·1	84·0	98·8
30–40 cm	3·3	1·1	148·0	76·5
40–50 cm	1·4	0·8	170·0	87·5

Mature forest

Despite a similar clay content the stability of *Pinus* forest aggregates is lower than that recorded for matorral, and may reflect the absence of hydrophobic exudates generated by the *Cistus*. A very distinctive feature of the *Pinus* forest area is the abundance of fungal hyphae occurring between the litter layer and the mineral soil horizons. Indeed, these forests are famous in Spain for mushroom growth in autumn. Fungal hyphae act as temporary binding agents. According to Tisdall and Oades (1982) fungal hyphae are sticky and retain their strength when stable wet aggregates from the field are dissected. Hyphae and fine roots hold particles together more or less equally in a three-dimensional network so that aggregates do not slake when wetted rapidly.

Arable

The effects of cultivation on soil aggregation and aggregate stability have been documented by various authors (Low, 1972; Grieve, 1980b). Tillage operations may break up soil aggregates or consolidate soil into larger aggregates depending on the prevailing soil-moisture conditions. In addition to shearing by agricultural implements, exposed soil aggregates may be broken down by raindrop impacts and by rapid wetting. This physical disruption exposes less accessible organic matter to microorganisms and stimulates oxidation causing a decline in soil organic matter and a decrease in the number of water-stable aggregates (Tisdall and Oades, 1982). In the seasonally arid climate of central Spain agricultural land is often left fallow for the summer months. Surface tillage to eliminate weed growth and conserve moisture may enhance organic-matter

oxidation. The organic carbon content of arable soils does appear to be significantly lower than adjacent *Cistus* matorral areas (Table II). The loss-on-ignition data, which provide an index of the amount of coarse and fine organic matter in the < 2·00 mm fraction, show little difference between the three land-use types. This may be explained by cereal stubble incorporation prior to sampling which seems to have had little beneficial impact on aggregate stability. The composition of the organic matter may therefore be critical.

In addition to the possible effect of hydrophobic substances on the *Cistus* aggregates, the contrast between the matorral and arable soils may reflect the textural and clay mineralogical composition of the surface soil horizons. The clay content of the arable soils was consistently higher (12–28 per cent) than immediately adjacent matorral sites (< 10 per cent). Although this is explicable in terms of selective removal of dispersed materials in the matorral area as discussed, deep ploughing by heavy agricultural machinery regularly brings up soil material of low organic carbon content from depths of *c.* 30 cm. Data for an undisturbed soil profile under matorral (Table VII) show clay contents for these subsurface horizons to range from 27–33 per cent with percentages of water-stable aggregates not too dissimilar to the surface horizons of the ploughed areas. This ploughing also appears to have changed the clay mineralogy of the surface soils giving rise to a high proportion of expandable clays (Table VII). In the undisturbed matorral profile *c.* 43 per cent of the < 2 μm material in the 20–30 cm horizon consisted of expandable material in contrast to *c.* 11 per cent for the 0–10 cm horizon. Results from the 0–10 cm horizon of the adjacent ploughed area shows *c.* 24 per cent expandable clay, illustrating the effect of cultivation.

Although in the undisturbed matorral profile the RSSI percentage and waterdrop data show no clear pattern with depth, the percentage of water-stable aggregates is very low for the subsurface horizons. This corresponds with a rise in clay content which remains constant from 20 to 50 cm (Table VII). The percentage of water-stable aggregates is particularly low for the 40–50 cm horizon, coinciding with a marked increase in the sodium adsorption rate, suggesting the dispersive impacts of expanding clays. On ploughing, these soil materials form large clods giving a high surface roughness and depression storage. With the onset of autumn rains these clods readily disperse with consequent surface sealing. On low-gradient slopes large pools of water remain for many weeks after rainfall, testifying to the very low permeability of these dispersed soils. On sloping sites, evidence of overland flow and erosion is widespread in cultivated areas.

CONCLUSIONS

This study has demonstrated the complexity of relationships between aggregate stability, soil properties and land management in central Spain. Whilst soil properties appear to be the fundamental controls of aggregate stability, both recent land-use histories and contemporary land-management practices are major factors modifying their impact. Evidence of present-day erosional losses under *Cistus* matorral are minimal but the low clay content of the surface horizon and the presence of lichen-encrusted stone lags testify to active erosion in the past. This was probably associated with intensive but poorly mechanized agricultural activity in the 1940s. The stable aggregates under *Cistus* may represent a lag of resistant aggregates, although hydrophobic substances from the *Cistus* may have increased soil-aggregate stability in the post-agricultural abandonment period. By contrast, laboratory rainfall-simulation test results show a clear separation of these *Cistus* aggregates from those under *c.* 40–50 year old *Pinus* forest planted in the post-abandonment period. These forest aggregates show an overlapping aggregate stability field with those from areas that remained under cultivation and are currently under intensive cereal production. This suggests that conifer afforestation may have provided some increase in soil aggregate stability in the post-abandonment period, possibly through the beneficial effects of fungal hyphae. However, the marked changes in cultivation techniques make such conclusions tentative.

Although tillage operations may lead to a decline in organic matter and reductions in aggregate stability, comparisons between areas at present under cereal cultivation and immediately adjacent *Cistus* matorral suggests that the deep ploughing associated with the modern, highly mechanized agricultural activity in the area may be significant. This deep cultivation draws up material from subsurface horizons rich in clay and dominated by expanding clay minerals. This mixing of surface and subsurface horizons has produced ground-surface conditions in which large soil clods created by ploughing of damp soil are rapidly dispersed

with the onset of rain, thus sealing the soil surface. On level areas water may lie for several weeks following rain, and on sloping sites overland flow and erosion are commonly observed during rainstorms.

As a result of EU agricultural policies, considerable areas of climatically marginal land in Spain are likely to come out of agricultural production and may be afforested or revert to matorral. This study has highlighted some of the interactions and feedbacks between soil properties and land management which have considerable implications for soil permeability, runoff generation and erosion.

ACKNOWLEDGEMENTS

The work was carried out as part of an EU funded research programme (EV5V-0041) concerned with land management and erosion limitation in the Iberian Peninsula. The authors would also like to thank Tim Absalom for cartographic work and the undergraduate students at Plymouth who, with their assistance and good humour, have made our field seasons in Spain such an enjoyable experience.

REFERENCES

Bergsma, E. and Valenzuela, C. R. 1981. 'Drop testing aggregate stability of some soils near Merida, Spain', *Earth Surface Processes and Landforms*, **6**, 309–318.
Blackman, J. D. 1992. 'Seasonal variation in the aggregate stability of downland soils', *Soil Use and Management*, **8**, 142–150.
British Standards Institution. 1975. *Methods of Test for Soils for Civil Engineering Purposes*, BS 1377, BSI, London.
Bryan, R. B. 1968. 'The development, use and efficiency of indices of soil erodibility', *Geoderma*, **2**, 5–26.
Bryan, R. B. 1976. 'Considerations on soil erodibility indices and sheetwash', *Catena*, **3**, 99–111.
Bryan, R. B., Govers, G. and Poesen, J. 1989. 'The concept of soil erodibility and some problems of assessment and application', *Catena*, **16**, 393–412.
Cammeraat, L. H. (Ed.) 1991. *Mediterranean Desertification and Land Use MEDALUS Field Manual* 3.1, University of Amsterdam, 115 pp.
De Meester, T. and Jungerius, P. D. 1978. 'The relationship between the soil erodibility factor K (universal soil loss equation), aggregate stability and micromorphological properties of soils in the Hornos area, S. Spain', *Earth Surface Processes*, **3**, 379–391.
De Ploey, J. and Poesen, J. 1985. 'Aggregate stability, runoff generation and interrill erosion', in Richards, K. S., Arnett, R. R. and Ellis, S. (Eds), *Geomorphology and Soils*, George Allen & Unwin, London, 99–120.
Espejo Serrano, R. 1985. 'The ages and soils of two levels of "raña" surfaces in central Spain', *Geoderma*, **35**, 223–239.
Farres, P. J. 1980. 'Some observations on the stability of soil aggregates to raindrop impact', *Catena*, **7**, 223–231.
Gallardo, J., Pérez-González, A. and Benayas, J. 1987. 'Paleosuelos de los piedemonte villafranquienses y de las terrazas pleistocenas de la región del valle del Henares—Alto Jarama', *Boletin Geológico y Minero*, **98**, 27–39.
González del Tanago, M., Canadas, N., Blanco, R. and Ternan, J. L. 1994. 'Erosión bajo diferentes cubiertas vegetales en un suelo de Rañas de Guadalajara', In Arnáez, J., Garcia-Ruiz, J. M. and Gómez Villar, A. (Eds), *Geomorfologia en España*, Sociedad Española de Geomorfologia, Logroño, 227–238.
Grieve, I. C. 1979. Soil aggregate stability tests for the geomorphologist,' *British Geomorphological Research Group Technical Bulletin*, **25**, 28 pp.
Grieve, I. C. 1980a. 'A comparison of aggregate stability test procedures in determining the stability of fine sandy soils in Fife, Scotland', *Catena*, **6**, 123–129.
Grieve, I. C. 1980b. The magnitude and significance of soil structural stability declines under cereal cropping', *Catena*, **7**, 79–85.
Imeson, A. C. and Jungerius, P. D. 1976. 'Aggregate stability and colluviation in the Luxembourg Ardennes; an experimental and micromorphological study', *Earth Surface Processes*, **1**, 259–271.
Imeson, A. C. and Verstraten, J. M. 1985. 'The erodibility of highly calcareous soil material from southern Spain', *Catena*, **12**, 291–306.
Imeson, A. C. and Vis, M. 1984. 'Seasonal variations in soil erodibility under different land-use types in Luxembourg', *Journal of Soil Science*, **35**, 323–331.
Imeson, A. C., Kwaad, F. J. P. M. and Verstraten, J. M. 1982. 'The relationship of soil physical and chemical properties to the development of badlands in Morocco', in Bryan, R. and Yair, A. (Eds), *Badland Geomorphology and Piping*, Geobooks, Norwich, 47–70.
Low, A. J. 1954. 'The study of soil structure in the field and the laboratory', *Journal of Soil Science*, **5**, 57–74.
Low, A. J. 1972. 'The effect of cultivation on the structure and either physical characteristics of grassland and arable soils (1945–1970)', *Journal of Soil Science*, **23**, 363–380.
Mason, B. J. and Andrews, J. B. 1960. 'Drop-size distributions from various types of rain', *Quarterly Journal of the Royal Meteorological Society*, **86**, 346–353.
Morgan, R. P. C. 1986. *Soil Erosion and Conservation*, Longmans Scientific and Technical, Harlow, UK, 298 pp.
Muñoz, M. J., Aldeanueva, R. A. and Arnaiz, J. M. R. 1989. 'El clima de la Provincia de Guadalajara. Paralelo 37°', *Revista de Estudios Geográficos*, **13**, 227–252.
Pérez-González, A. and Gallardo, J. 1987. 'La Raña al sur de la Somosierra y Sierra de Ayllón: un piedemonte escalonado del Villafranquiense medio', *Geogaceta*, **2**, 29–32.
Sugimura, Y. and Suzuki, Y. 1988. 'A high temperature catalytic oxidation method for the determination of non-volatile dissolved organic carbon in sea water by direct injection of a liquid sample', *Marine Chemistry*, **24**, 105–131.
Sullivan, L. A. 1990. 'Soil organic matter, air encapsulation and water-stable aggregation', *Journal of Soil Science*, **41**, 529–534.

Ternan, J. L., Williams, A. G. and González del Tanago, M. 1994. 'Soil properties and gully erosion in the Guadalajara Province, Central Spain', in Rickson, J. (Ed.), *Conserving Soil Resources: European Perspectives*, CAB International, Oxford, 56–69.

Tisdall, J. M. and Oades, J. M. 1982. 'Organic matter and water stable aggregates in soils', *Journal of Soil Science*, **33**, 141–163.

Vardour, J. 1979. *La Région de Madrid, Altérations, Sols et Paleosols*, Contribution à l'étude géomorphologique d'une région mediterraneenne semi-aride, Editions Ophrys, A, ix, France, 390 pp.

Yoder, R. E. 1936. 'A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses,' *Journal of the American Society of Agronomy*, **28**, 337–351.